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## PARTICLES IN LOOPS – FROM ELECTRONS TO TOP QUARKS <sup>1</sup>

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### ABSTRACT

This article, in memory of Professor Hiroshi Suura, is devoted to the effects of particles in loops, ranging from quantum electrodynamics to precise tests of the electroweak theory and CP violation.

### INTRODUCTION

I owe an enormous debt to Hiroshi Suura. It was partly work [1] on the subject of this article that led him to bring me to the University of Minnesota, where I spent 13 pleasant years. He was an early collaborator [2], teaching me the value of clear thinking and careful statements. Throughout the years, he was a constant source of good ideas, sound judgement, and friendly advice. He was responsible for the contacts that led to my first visit to Japan in 1973, during which the generous hospitality my family and I received led us to return time and again to a country for which we have great love and admiration. During one such visit in 1981 I was privileged to meet Hiroshi's sister and brother-and-law on the occasion of a Japanese Physical Society meeting in Hiroshima at the end of March. I am thus especially honored to be able to pay tribute to Hiroshi's memory for a similar meeting eighteen years later. I miss him greatly.

I shall not discuss Hiroshi's important contributions to the theory of infrared corrections [3]. This work has been central to a wide variety of experiments in elementary particle physics, particularly those involving electrons. Many of the precise measurements I shall describe could not have been done without it. However, another theme running through Hiroshi's work and connecting it to the major issues of today's particle physics is the idea of "particles in loops." One of his most-quoted results concerns the effect of electron loops in the calculation of the muon's anomalous magnetic moment  $a_\mu$  [4]. This leads to a difference between  $a_\mu$  and the corresponding quantity  $a_e$  for the electron, which was confirmed in beautiful experiments at CERN [5] and is still the subject of intense scrutiny [6]. Hiroshi once admitted his reluctance to be

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<sup>1</sup>Dedicated to the memory of Professor Hiroshi Suura. Based on a colloquium in his honor at the University of Minnesota, 1 June 1994, updated to February 1999.

known for a calculation which took him such a short time. But his key contribution was not only in performing the calculation, but in being able to do so and in knowing what calculation to perform.

The effects of “particles in loops” indeed permeate almost all of today’s high energy physics. They have allowed us to make fundamental discoveries about the properties of quarks, to anticipate the charmed quark’s existence and the top quark’s mass, and to understand, at least in part, the violation of CP symmetry. This article briefly reviews those effects. For more technical details (some of which will be updated here) see, e.g., Ref. [7]. Many of the historical references are taken from [8].

In Section II we discuss vacuum polarization and radiative corrections. Section III is devoted to specific effects of quarks and leptons in loops. We review electroweak unification in Section IV, and CP violation in Section V. Some speculations on composite Higgs bosons and composite fermions occupy Sections VI and VII, respectively. Section VIII summarizes.

## II. VACUUM POLARIZATION AND RADIATIVE CORRECTIONS

### A. Vacuum polarization

The large positive charge of a nucleus “polarizes the vacuum.” Virtual electrons are attracted to the nucleus, while virtual positrons are repelled. A test charge at large distances sees the nucleus screened by the electrons, while at short distances it penetrates the screening cloud and sees a larger charge. In quantum electrodynamics this may be thought of as the effect of an electron-positron “loop” in the photon propagator. A direct calculation of this effect finds it to be infinite! However [9], one can circumvent this difficulty by comparing *ratios* of effective charges at two different distance scales. Defining the fine-structure constant  $\alpha \equiv e^2/4\pi\hbar c$  in terms of the charge  $e$ , and momentum scales  $\mu_i = \hbar/r_i$  in terms of distance scales  $r_i$  ( $i = 1, 2$ ), the lowest-order result is

$$\alpha(\mu_1) = \frac{\alpha(\mu_2)}{1 - (\alpha/3\pi) \ln(\mu_1^2/\mu_2^2)} \quad (1)$$

and hence  $\alpha(\mu_1) > \alpha(\mu_2)$  for  $\mu_1 > \mu_2$ . The electromagnetic interaction thus becomes stronger at higher momentum scales (shorter distance scales). For an electron bound in hydrogen [10], vacuum polarization leads to a stronger attraction in a  $2S$  state than in a  $2P$  state, leading to a splitting between the levels of  $\Delta E(2S - 2P) = -27$  MHz.

### B. The Lamb shift

The experimental value of the  $2S - 2P$  splitting in hydrogen was first measured by W. Lamb in 1947 [11]. In addition to the vacuum polarization effect mentioned above, there is a much more substantial shift in the other direction, in which an electron emits and reabsorbs a virtual photon while interacting with the nucleus [12]. The most recent experimental values for the splitting are  $1057.8514 \pm 0.0019$  MHz

[13],  $1057.845 \pm 0.009$  MHz [14], and  $1057.839 \pm 0.012$  MHz [15], to be compared with the theoretical calculation [16] of  $1057.838 \pm 0.006$  MHz.

### C. The electron $g$ -factor

The process in which an electron emits and reabsorbs a virtual photon while interacting with an external field also alters its magnetic moment  $\mu_e$ , expressed in terms of its spin  $\vec{S}_e$  via a quantity  $g$ :  $\vec{\mu}_e = \vec{S}_e g e / (2m_e c)$ . In the Dirac theory of the electron,  $g = 2$ . The correction to this result is [17, 18]

$$\left. \frac{g-2}{2} \right|_e = \frac{\alpha}{2\pi} - 0.328\,476\,965 \left( \frac{\alpha}{\pi} \right)^2 + \dots = (1\,159\,652\,140 \pm 27) \times 10^{-12} \quad . \quad (2)$$

The lowest-order term is due to Schwinger [19]; the corrections have been calculated up to  $\mathcal{O}(\alpha^5)$ . The error is due mainly to uncertainty in  $\alpha$ . The latest experimental result [20] is

$$\left. \frac{g-2}{2} \right|_e = (1\,159\,652\,188 \pm 3) \times 10^{-12} \quad . \quad (3)$$

The agreement with theory, and that of the Lamb shift mentioned earlier, are examples of the successful application of quantum field theory to electrodynamics.

### D. The muon $g$ -factor

The second term on the right-hand side of Eq. (2),  $-0.328 \dots (\alpha/\pi)^2$ , contains a contribution from the process in which an electron emits and reabsorbs a virtual photon while interacting with the external field, and this virtual photon itself is subject to the vacuum polarization effect (1). The virtual photon thus can be affected by any charged particle-antiparticle pair in a loop. The pair providing the major contribution to the electron  $g$ -factor is an electron-positron pair; other heavier particles contribute, but not significantly to this order.

For the muon  $g$ -factor, the situation is different. Here, both the  $e$ -loop and the  $\mu$ -loop are important. The major effect of the  $e$ -loop can be regarded as an effective modification of the leading-order  $\alpha/2\pi$  correction:

$$\frac{\alpha}{2\pi} \rightarrow \frac{\alpha}{2\pi} \left[ 1 - \frac{\alpha}{3\pi} \left( \ln \frac{m_\mu^2}{m_e^2} - \text{const} \right) \right]^{-1} \quad (4)$$

as dictated by the correction (1). The fine-structure constant “runs” as a function of distance (i.e., momentum) scale. The theoretical expression for the muon  $g$ -factor thus differs from that for the electron at second order in  $\alpha$  [4]. This observation of Hiroshi’s was a shining example of how particles in loops *other than those under direct study* can affect measurable physics. We shall see a number of more recent applications of this idea in subsequent sections.

The present theoretical expression [21, 22, 23] for the muon  $g$ -factor is

$$\left. \frac{g-2}{2} \right|_{\mu} = \frac{\alpha}{2\pi} + 0.765\,857\,388(44) \left( \frac{\alpha}{\pi} \right)^2 + \dots = (11\,659\,159.6 \pm 6.7) \times 10^{-10} \quad , \quad (5)$$

to be compared with the experimental value [24]  $(11\,659\,230 \pm 85) \times 10^{-10}$ . At this level of accuracy one must consider the effects of not only electrons and muons in loops, but also quarks. A new experiment at Brookhaven National Laboratory seeks to probe  $a_{\mu}$  20 times more precisely, reaching enough sensitivity to probe even the effect of weakly interacting particles in loops [6].

### III. QUARKS AND LEPTONS IN LOOPS

#### A. Neutral pion decay

The decay of the neutral pion  $\pi^0$  is governed by a triangle “anomaly” diagram [25]. The  $\pi^0$  dissociates into a quark-antiquark pair which then annihilates into two photons. The process thus counts the number of quarks  $q$  traveling around the loop, weighted by the product of their coupling to the  $\pi^0$  and the square of their charges  $Q(q)$ . Since the  $\pi^0$  is represented in the quark model as  $(u\bar{u} - d\bar{d})/\sqrt{2}$ , the amplitude for  $\pi^0 \rightarrow \gamma\gamma$  thus measures  $S = \sum [Q(u)^2 - Q(d)^2]$ , where the sum is taken over the number of quark species (“colors”, if one wishes). For 3 colors of fractionally charged (“Gell-Mann–Zweig”) [26] quarks,  $S = 3[(2/3)^2 - (-1/3)^2] = 1$ .

An alternative quark model involves integrally charged (“Han–Nambu”) quarks [27]: Two colors of  $u$  quark have  $Q(u_{1,2}) = 1$  while one color has  $Q(u_3) = 0$ ; two colors of  $d$  quarks have  $Q(d_{1,2}) = 0$  while one color has  $Q(d_3) = -1$ . The amplitude for  $\pi^0 \rightarrow \gamma\gamma$  turns out to be the same [28]. Hiroshi was intrigued with this possibility [29], and we had many interesting discussions on the subject. It is interesting that quarks at high density may undergo a color-flavor “locking” which converts them from the Gell-Mann–Zweig to the Han–Nambu variety [30]. It is one of many results in the past year on which I would have enjoyed hearing Hiroshi’s opinion.

#### B. Triangle anomalies and fermion families

The triangle anomaly’s contribution to trilinear gauge boson couplings is undesirable in unified theories of the weak and electromagnetic interactions. In order that it vanish, the sum of  $I_{3L}Q^2$  over all fermions must equal zero. Here  $I_{3L}$  is “left-handed isospin,” equal to  $1/2$  for left-handed  $u$  quarks and neutrinos,  $-1/2$  for left-handed  $d$  quarks and charged leptons  $\ell^-$ , and zero for all left-handed antiparticles. This sum vanishes for quarks and leptons within a single “family,” with respective contributions of  $2/3$ ,  $-1/6$ ,  $0$ , and  $-1/2$  from, e.g.,  $u$ ,  $d$ ,  $\nu_e$ ,  $e^-$ . The need for the charmed quark in the second family  $c$ ,  $s$ ,  $\nu_{\mu}$ ,  $\mu^-$  was in part argued [31] on the basis of anomaly cancellation. Definitive evidence for the charmed quark was presented within two years [32], in the form of a  $c\bar{c}$  bound state, the  $J/\psi$  particle. (There had already

been indications of charm in cosmic ray events [33], which were taken very seriously in Japan [34].)

The anomaly cancellation confirmed by the charmed quark’s discovery was short-lived. A third lepton  $\tau$  was announced within the year [35]. A third pair of quarks  $t$ ,  $b$  (proposed earlier [36] to explain CP violation; see Sec. V) was then required to restore the cancellation [37]. The  $b$  was discovered in 1977 [38] and the  $t$  in 1994 [39], both at Fermilab. The high mass of the top quark,  $m_t = 174 \pm 5 \text{ GeV}/c^2$  [40], makes it a particularly important player in many loop diagrams, in ways which we now describe.

## IV. ELECTROWEAK UNIFICATION

### A. The $SU(2) \times U(1)$ gauge theory

Fifty years ago it was popular to talk of the “four forces of Nature”: gravity, electromagnetism, the weak force, and the strong force. We sometimes forget that Newton’s theory of gravity itself was a unification of terrestrial and celestial phenomena, while Maxwell’s theory of electromagnetism, building upon Faraday’s experiments, unified previously distinct electrostatic and magnetic results.

During Hiroshi’s career we have seen the successful unification of the weak and electromagnetic interactions [41]. In analogy with the view of electromagnetism as arising from photon exchange, we now view the weak interactions (those responsible, for example, for nuclear beta-decay) as arising from the exchange of charged, massive  $W$  bosons. The unified theory allows self-consistent calculations of weak processes at high energies and to higher orders of perturbation theory. The prices to pay are that (1) the  $W^\pm$  must exist (it was discovered in 1983 [42]), and (2) the simplest version also requires a massive *neutral* boson, the  $Z^0$  (also discovered in 1983 [43]). The exchange of a  $Z$  leads to new weak charge-preserving interactions, first seen in 1973 [44].

The new theory has the symmetry  $SU(2) \times U(1)$ , broken to  $U(1)$  of electromagnetism by the mechanism which gives the  $W^\pm$  and  $Z^0$  bosons their masses while leaving the photon massless. The neutral  $SU(2)$  boson,  $W^0$ , and the  $U(1)$  boson,  $B^0$ , mix with an angle  $\theta$  to give the massless photon and the massive  $Z^0$ .

Since quarks of the same charge can mix with one another, the charge-changing transitions involving  $W$  emission and absorption connect all quarks of charge  $2/3$  with all quarks of charge  $-1/3$  through a unitary matrix  $V$ , the *Cabibbo-Kobayashi-Maskawa* (CKM) [36, 45] matrix. As a result of the unitarity of  $V$ , the couplings of  $Z^0$  remain diagonal in quark “flavor” even after mixing. The only corrections to the flavor-diagonal nature of neutral weak processes come at higher orders of perturbation theory, through particles in loops.

### B. Main electroweak corrections

A major source of corrections to the electroweak theory, which can now be probed

as a result of the precision of varied experiments, is the effect of particles in loops in the photon,  $W$ , and  $Z$  propagators.

All charged fermions can contribute in pairs to the photon charge renormalization (the effect of Eq. (1) and its higher-order generalizations). Whereas at long distances the fine structure constant  $\alpha$  is approximately  $1/137.036$ , when probed at the scale of the  $Z^0$  mass it is [23]  $\alpha(M_Z) \simeq 1/128.9$ . This simple correction substantially improves the predictions of the unified theory for the  $W$  and  $Z$  masses, given the value of the electroweak mixing parameter  $\sin^2 \theta = 0.23156 \pm 0.00019$  measured in a wide variety of neutral-current processes [46].

The  $W$  and  $Z$  propagators receive large contributions from loops involving the third quark family as a result of the large top quark mass. The prediction of the lowest-order electroweak theory,  $M_W/M_Z = \cos \theta$ , is modified to [47]

$$\frac{M_W^2}{M_Z^2} = \rho \cos^2 \theta \quad , \quad \rho \simeq 1 + \frac{3G_F m_t^2}{8\pi^2 \sqrt{2}} \quad . \quad (6)$$

Here  $G_F = 1.16639 \times 10^{-5} \text{ GeV}^{-2}$  is the Fermi coupling constant, and  $m_t = 174 \pm 5 \text{ GeV}/c^2$  is the top quark mass. The parameter  $\rho$  is then about a percent, and multiplies the amplitude of every weak neutral-current process. Consequently, each of these processes probes  $m_t$ , so it was possible to anticipate its value (modulo effects of the Higgs boson, which we discuss next) before it was measured directly.

### C. The Higgs boson and its effects

A consequence of endowing the  $W$  bosons with mass is that the elastic scattering of longitudinally polarized  $W^+W^-$  does not have acceptable high-energy behavior. It would violate the unitarity of the  $S$ -matrix (i.e., would violate probability conservation) at high energies unless a spinless neutral boson (the ‘‘Higgs boson’’) exists below a mass of  $M_H \simeq 1 \text{ TeV}/c^2$  [48]. The discovery of such a boson is a prime motivation for multi-TeV hadron colliders such as the Large Hadron Collider (LHC) now under construction at CERN. Searches in  $e^+e^-$  collisions at LEP find no evidence for the Higgs boson below nearly  $100 \text{ GeV}/c^2$  [46], but precision electroweak experiments seem to favor a Higgs mass near this lower limit.

Virtual Higgs boson can contribute to loops in the  $W$  and  $Z$  propagators, thus affecting not only  $\rho$  but a parameter  $S$  [49] which expresses the difference between electroweak results at low momentum transfers and those probed at the higher momentum scale of  $Z^0$  decays. One can calculate all electroweak observables for nominal values of  $m_t$  and  $M_H$  (say,  $175$  and  $300 \text{ GeV}/c^2$ , respectively) and then ask how they deviate from those nominal values, thereby specifying constraints on the parameters  $\rho$  and  $S$ . Given the observed value of  $M_Z$ , one obtains [7] a nominal value of  $\sin^2 \theta = 0.2321 \equiv x_0$ . It is conventional to define  $\Delta\rho = \alpha T$ , and one then finds [49]

$$T \simeq \frac{3}{16\pi x_0} \left[ \frac{m_t^2 - (175 \text{ GeV})^2}{M_W^2} \right] - \frac{3}{8\pi(1 - x_0)} \ln \frac{M_H}{300 \text{ GeV}} \quad . \quad (7)$$

Note the quadratic dependence on  $m_t$ , but only logarithmic dependence on  $M_H$ . That is why electroweak observables were able to predict a top quark mass (with some uncertainty) despite the absence of information about the Higgs boson mass. The “ $S$ ” parameter is logarithmic in both  $m_t$  and  $M_H$ . As in the case of  $T$ , it can be defined to be zero for nominal values of  $m_t$  and  $M_H$ , so that deviations of  $S$  from zero are indicative of new physics.

Fits to a wide variety of electroweak parameters are performed periodically as these data become more and more precise. Such data include the ratio of charge-preserving to charge-changing deep inelastic cross sections for neutrinos on matter, the  $W$  mass (measured at LEP and Fermilab), and a host properties of the  $Z$  boson, such as its mass, width, branching ratios, and decay asymmetries (measured at LEP and the Stanford Linear Collider). Since the Higgs boson appears in loops, and the top quark mass is fairly well pinned down, such fits can constrain the (logarithm of the) Higgs boson mass. A recent fit [46] finds  $M_H = 84^{+91}_{-51}$  GeV/ $c^2$  [50], or  $M_H < 280$  GeV at 95% confidence level. Of course, much of this range is already ruled out by the direct searches mentioned earlier.

#### D. Effects of other new particles; atomic parity violation

The  $S$  and  $T$  parameters respond differently to new particles. The  $T$  parameter is affected by the presence of pairs of left-handed fermions with charges differing by one unit (such as  $t$  and  $b$ ) whose masses also differ from one another (as in the case of  $t$  and  $b$ ). However, it is not affected by new degenerate pairs. The  $S$  parameter, on the other hand, *is* affected. It is a good probe of new particles in loops, even if these particles hide their contributions to  $T$  by being degenerate in mass, and no matter how heavy these particles may be [49].

One probe of  $S$  is almost insensitive to  $T$  [51, 52]. Atomic transitions can violate mirror symmetry (parity) as a result of the interference of photon and  $Z$  exchange. The coherent coupling of the  $Z$  to a nucleus is expressed in terms of the *weak charge*, given approximately as  $Q_W \simeq \rho(N - Z - 4Z \sin^2 \theta)$ , where  $N$  and  $Z$  are the number of neutrons and protons in the nucleus. Very recently, a new result in atomic cesium has been presented [53]:  $Q_W = -72.06 \pm 0.28 \pm 0.35$ , where the first error is experimental and the second is theoretical. This result is  $2.5\sigma$  from the theoretical prediction [51] of  $Q_W = -73.20 \pm 0.13$ . However, the deviation is opposite in sign from that caused by the the most naive addition of particles in loops! This result bears watching. The experiment has been pushed about as far as it can go, so it is now incumbent upon the theorists to check their calculations (and the refinements of them in Ref. [53] that reduced the theoretical error so dramatically from previous values).

### V. CP VIOLATION

#### A. The neutral kaon system

The neutral kaon  $K^0$  and its antiparticle  $\bar{K}^0$  are an example of a degenerate two-state system, with the degeneracy lifted by coupling to final states. So, too,

are the two equal-frequency modes of a circular drum with a single nodal line along the diameter. Any basis may be chosen in which the nodal line for one mode is perpendicular to that for the other. For example, let the  $K^0$  correspond to the mode with the node at 45 degrees with respect to the  $x$ -axis; then the  $\bar{K}^0$  will correspond to the orthogonal mode.

Now a fly lands on the drum-head somewhere on the  $x$  axis. The two degenerate states will be mixed and split in such a way that the fly couples to one mode (with the node perpendicular to the  $x$ -axis) and not the other (with the node along the  $x$ -axis). The fly is like the  $\pi\pi$  final state, and the eigenstates are

$$K_1 = \frac{K^0 + \bar{K}^0}{\sqrt{2}} (\rightarrow \pi\pi) \quad , \quad K_2 = \frac{K^0 - \bar{K}^0}{\sqrt{2}} (\not\rightarrow \pi\pi) \quad . \quad (8)$$

Since the  $\pi\pi$  system in the decay of the spinless kaons has even  $CP$ , where  $C$  is charge-reversal and  $P$  is parity, or space inversion, the states with definite mass and lifetime in the limit of  $CP$  conservation are  $K_1$  and  $K_2$ . The  $K_1$  is thus much shorter-lived than the  $K_2$ , which has to decay in some other manner than  $\pi\pi$  [54].

In 1964, Christenson, Cronin, Fitch, and Turlay [55] discovered that the long-lived kaon *also* decays to  $\pi\pi$ . One could thus represent the states of definite mass and lifetime as

$$K_S \simeq K_1 + \epsilon K_2 \quad , \quad K_L \simeq K_2 + \epsilon K_1 \quad . \quad (9)$$

The parameter  $\epsilon$  has a magnitude of a bit over  $2 \times 10^{-3}$  and a phase of about  $\pi/4$ . Where does it come from?

One possibility was suggested right after the discovery of  $CP$  violation: A new “superweak” interaction [56] directly mixes  $K^0$  and  $\bar{K}^0$ , with a phase which leads to  $CP$  violation. However, Kobayashi and Maskawa [36] proposed that phases in the weak couplings of quarks to  $W$  bosons generate  $\epsilon$  through loop graphs. Three quark families are needed for non-trivial phases. The Kobayashi-Maskawa proposal thus entailed the existence of the top and bottom quarks, later discovered at Fermilab.

The loop graphs in question are ones in which, for example, a  $K^0 = d\bar{s}$  undergoes a virtual transition via  $W$  exchange to a pair  $q_i\bar{q}_j$ , where  $q_i$  and  $q_j$  are any charge-2/3 quark:  $u, c, t$ . The  $q_i\bar{q}_j$  pair can then exchange a  $W$  of the opposite charge to become  $\bar{K}^0 = s\bar{d}$ . The top quark provides the dominant contribution to this process because of its large mass.

The Kobayashi-Maskawa (KM) theory of  $CP$  violation has recently survived two key tests, the most recent of which seems to have firmly buried the superweak theory. These are results which Hiroshi would have enjoyed.

## B. $CP$ violation in $B$ meson decays

The first new result concerns  $CP$  violation in the system of neutral  $B$  mesons, predicted to be large in the KM theory. The same loop diagrams which mix neutral kaons also mix  $B^0 = d\bar{b}$  and  $\bar{B}^0 = b\bar{d}$ . The phase of the mixing amplitude is predicted within rather narrow limits by fits to various weak-decay and mixing data.



The best sign of CP violation in the  $B$  meson system was anticipated [57] to be the following asymmetry in rates:

$$A(J/\psi K_S) \equiv \frac{\Gamma(\bar{B}^0|_{t=0} \rightarrow J/\psi K_S) - \Gamma(B^0|_{t=0} \rightarrow J/\psi K_S)}{\Gamma(\bar{B}^0|_{t=0} \rightarrow J/\psi K_S) + \Gamma(B^0|_{t=0} \rightarrow J/\psi K_S)} \neq 0 \quad . \quad (10)$$

Here the subscript indicates that the flavor of the neutral  $B$  is identified at the time of its production; it oscillates between  $B^0$  and  $\bar{B}^0$  thereafter as a result of  $B^0$ – $\bar{B}^0$  mixing. The asymmetry arises from the interference of the mixing amplitude with the decay amplitude. The decay  $B^0 \rightarrow J/\psi K_S$  can occur either directly or through the sequential process  $B^0 \rightarrow \bar{B}^0 \rightarrow J/\psi K_S$ , which imposes a modulating amplitude on the direct decay. The sign of this modulating amplitude is opposite to that in  $\bar{B}^0 \rightarrow B^0 \rightarrow J/\psi K_S$  (interfering with the direct  $\bar{B}^0 \rightarrow J/\psi K_S$  process), and so a difference arises in both time-dependent and time-integrated rates.

A recent result from the CDF Collaboration at Fermilab [58] observes the asymmetry at about the  $2\sigma$  level with the value predicted by the KM theory. Both SLAC and KEK are constructing “ $B$ -factories” to observe this asymmetry (and many others) at a compelling statistical level, and many other experiments (e.g., at Cornell, LEP, DESY and Fermilab) may have something to say soon on CP-violation in  $B$  decays.

### C. Demise of the superweak theory

The second new result concerns the most significant result on the decays of neutral kaons since the discovery that they violated CP in 1964. Since then, all CP-violating effects in the neutral kaon system could be parametrized by the single quantity  $\epsilon$  in Eq. (9). If that were so, one should see no difference between the CP-violating decays  $K_L \rightarrow \pi^+\pi^-$  and  $K_L \rightarrow \pi^0\pi^0$  when normalized by the corresponding  $K_S$  rates. Thus, the double ratio

$$R \equiv \frac{\Gamma(K_L \rightarrow \pi^+\pi^-)/\Gamma(K_S \rightarrow \pi^+\pi^-)}{\Gamma(K_L \rightarrow \pi^0\pi^0)/\Gamma(K_S \rightarrow \pi^0\pi^0)} \quad (11)$$

should equal 1. In the KM theory it can differ from 1 by up to a percent. A “direct” decay amplitude, parametrized by a quantity  $\epsilon'$ , can violate CP. The double ratio is  $R = 1 + 6 \operatorname{Re}(\epsilon'/\epsilon)$ . The superweak theory has no provision for  $\epsilon'$ .

Two previous experiments gave conflicting results on whether  $\epsilon'$  was nonzero:

$$\operatorname{Re}(\epsilon'/\epsilon) = (7.4 \pm 5.9) \times 10^{-4} \quad (\text{Fermilab E731}) \quad [59] \quad , \quad (12)$$

$$\operatorname{Re}(\epsilon'/\epsilon) = (23 \pm 6.5) \times 10^{-4} \quad (\text{CERN NA31}) \quad [60] \quad . \quad (13)$$

A new experiment at Fermilab has now confirmed the CERN result with far more compelling statistics, finding

$$\operatorname{Re}(\epsilon'/\epsilon) = (28.0 \pm 4.1) \times 10^{-4} \quad (\text{Fermilab E832}) \quad [61] \quad . \quad (14)$$

The superweak theory is definitively ruled out. The magnitude of the effect is on the high end of the most recent theoretical range [62], but this may merely represent a shortcoming of methods to estimate hadronic matrix elements rather than any intrinsic limitation of the KM theory. The new result will probably reduce the uncertainty on the parameters of the CKM matrix.

#### D. Alternative sources of CP violation

So far the Kobayashi-Maskawa theory of CP violation has survived experimental tests. But what if it is eventually ruled inconsistent or incomplete? Many other theories are lurking in the wings, including superweak *contributions* to CP violation (clearly not the whole story), effects of right-handed  $W$  bosons, and multi-Higgs models. These can be tested by a host of forthcoming experiments, including those on rare kaon and  $B$  meson decays, searches for transverse muon polarization in the decays  $K \rightarrow \pi\mu\nu$ , searches for neutron and electron electric dipole moments, and searches for CP violation in decays of hyperons and charmed particles. The field is very rich and full of experimental opportunities.

### VI. COMPOSITE HIGGS BOSONS

The  $SU(2) \times U(1)$  electroweak gauge theory must be supplemented by a mechanism for breaking the symmetry. The standard (“Higgs”) mechanism involves the introduction of an  $SU(2)$  doublet of complex scalar fields, or four scalar mesons. Three of the four scalars become the longitudinal components of the  $W$  and  $Z$ , and one remains as the physical Higgs boson. With more than one doublet, there will be additional observable scalar fields in the spectrum.

The Higgs fields interact with one another quartically in the Lagrangian. In the presence of any physics beyond the electroweak scale, such as arises in “grand unifications” of the electroweak and strong interactions, such a theory cannot be fundamental. New physics must enter at a mass scale of a TeV or less in order that the Higgs boson mass not receive large radiative corrections from the higher mass scale. Independently of grand unified theories, the quartic Higgs interaction itself has undesirable high-energy behavior, so that the only theory which makes sense is the “trivial” one in which the quartic interaction vanishes.

One approach to this problem is provided by supersymmetry, which provides a set of “superpartners” to the currently observed particles, differing from them by half a unit of spin. The quartic interaction is then not fundamental, and the superpartners cancel the large radiative corrections. Another approach is to postulate that the Higgs fields themselves are composite. This idea [63], known as “technicolor,” envisions the Higgs fields as fermion-antifermion pairs, with the new fermions bound by some new superstrong force, in the same way that pions are made of quarks bound by the force of quantum chromodynamics (QCD). In analogy with QCD, which implies a low-energy pion-pion quartic interaction which is not really fundamental, the Higgs boson quartic potential is then just a consequence of some more fundamental underlying theory.

Properties of the new technifermions can be learned by an argument based on particles in loops. Their charges must be such as to ensure anomaly cancellation in the decay of a longitudinal  $Z$  to two photons. If one has a single  $SU(2)$  doublet  $(U, D)$  of technifermions (occurring in some number of “techni”-colors), the vanishing of  $Q(U)^2 - Q(D)^2$  then requires  $Q(U) = 1/2$ ,  $Q(D) = -1/2$ . This was the original solution of “minimal technicolor” [63, 64]. It was abandoned because there seems to be no evidence for fundamental fermions with charges  $\pm 1/2$ , and because the minimal model only explains the masses of  $W$  and  $Z$ , not of quarks and leptons. Attempts to “extend” technicolor to a theory of quark and lepton masses [65] introduce many new particles in loops and thus run afoul of the constraints from precise electroweak experiments mentioned in Sec. IV [49]. In the next section I will propose a solution [66] to which Hiroshi might have been sympathetic, in view of his early efforts [67] to uncover the substructure of particles.

## VII. COMPOSITE FERMIONS

Suppose the minimal techniquarks  $U$  and  $D$  of Sec. VII are the carriers of the weak isospin (the  $SU(2)$  quantum number) in quarks and leptons. A formula for the charge of quarks and leptons which suggests this identification is [68]  $Q = I_{3L} + I_{3R} + (B - L)/2$ , where  $I_{3L}$  is left-handed isospin,  $I_{3R}$  is right-handed isospin,  $B$  is baryon number, and  $L$  is lepton number. We imagine  $U, D$  to carry  $I_{3L}$  and  $I_{3R}$  since these quantum numbers are naturally correlated with quark or lepton spin. (Note that  $I_{3L} + I_{3R}$  is always equal to  $+1/2$  for up quarks and neutrinos and  $-1/2$  for down quarks and charged leptons.) The  $(B - L)/2$  contribution to the charge then has to be carried by “something else”. Let it be a scalar  $\bar{S}_q$  with charge  $1/6$  for three colors of quarks or  $\bar{S}_\ell$  with charge  $-1/2$  for leptons. The scalars thus belong to an  $SU(4)_{\text{color}}$  group first proposed by Pati and Salam [69]. A  $u$  quark is then  $U\bar{S}_q$ , while an electron is  $D\bar{S}_\ell$ . Tests of this model (or of others of quark and lepton substructure) are possible at the highest LEP energies, forthcoming Tevatron experiments, and future hadron and lepton colliders.

## VIII. SUMMARY

When this talk was originally given nearly five years ago at Minnesota, the top quark had just been discovered, confirming a prediction based on its role in loop diagrams. Since then there have been great strides in confirming other predictions of loop diagrams, including hints of CP violation in  $B$  meson decays and the overthrow of the superweak theory of CP violation. Experiments in atomic parity violation suggest that we may not know the full story of effects of particles in loops, but the presence of at least one puzzling result is what makes our field interesting. Hiroshi would have enjoyed the recent developments. On this occasion I extend good wishes to Akiko and to his colleagues, and thank them for the opportunity to honor his memory.

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